Use of NASA Remote Sensing datasets in NOAA National Weather Service River Forecast Centers' Hydrologic Modeling System

Earth Science Office (VP61)
NASA Marshall Space Flight Center
Huntsville, Alabama 35805

Acknowledgments

This work was supported by the NASA Earth Science Applications Directorate, Water Management Program. The work has been conducted at NASA Marshall Space Flight Center and NOAA National Weather Service Office of Hydrologic Development.

Team Members

Pedro Restrepo-Principal Investigator

NASA MSFC
Ashutosh Limaye
Mohammad Al-Hamdan
William Crosson
Maury Estes
Charles Laymon
Douglas Rickman

NOAA NWS OHD
Michael B. Smith

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Executive Summary

The National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) has a mandate to provide hydrologic forecasts to the Nation. Operational river forecasts are generated using a hydrologic modeling system at 13 River Forecast Centers (RFCs) throughout the country on a continuous basis for approximately 4,000 river locations. NASA satellite-based Earth Science observations can be exploited in an Integrated Systems Solutions Investigation in Water Management to improve operational river forecasts delivered by NOAA NWS RFC's Decision Support System (DSS). Improvements in streamflow forecasts can be evaluated as a direct result of assimilation of NASA's remotely sensed data products to better quantify hydrologic abstractions conducted on an operational basis by NWS RFCs. In the benchmarking process, improvements brought by the use of NASA data in the DSS are quantified. The study is done in full collaboration with the NWS Hydrology Laboratory (HL), the research center responsible for producing, maintaining and upgrading the hydrologic modeling systems for the RFCs. A systems engineering approach including Evaluation, Verification and Validation, and Benchmarking processes will be used to assimilate NASA data into the DSS and quantify the impact that ESE data products and models have on streamflow forecasting. An existing investigation has allowed the team to become familiar with the NWS RFC decision support system and the manner in which the HL and RFCs interact, which contributes to managing risks. The Hydrology Laboratory is interested in extending the use of remote observations in several areas for improved estimates of evapotranspiration, frozen soil processes and mapping, and flood inundation mapping and monitoring. One area of interest is evaporation estimates from remotely sensed observations for use in the hydrologic modeling. NWSRFS has lost previously available functionality due to discontinued observations needed in evaporation computations. Replacement of those observations is HL's top priority, and that could be accomplished with remote observations from space. NASA's cloud mask product derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) can be used to replace discontinued ground observations of cloud cover. This effort is directly associated with the NASA Water Management Program's roadmap by assimilating NASA's observational capabilities to improve the accuracy of water management predictions of another federal agency in operational decision-making.

1. Introduction

1.1. The Water Management Need

The National Oceanic and Atmospheric Administration (NOAA), National Weather Service (NWS) is mandated to provide hydrologic services to the Nation. Missions of the NWS include a.) providing river and flood forecasts and warnings for the protection of life and property, and b.) providing basic hydrologic forecast information for the Nation's economic and environmental well-being. Hydrologic observations and operational streamflow forecasts are carried out at 13 River Forecasting Centers (RFCs) throughout the country on a continuous basis for approximately 4,000 river locations. These forecasts are generated by each of the RFCs using the NWS River Forecast System (NWSRFS), NWS's Decision Support System (DSS) for hydrologic forecasting. The forecasts are passed on to local NWS Weather Forecast Offices for dissemination to the general public.

1.2. Partnering with NOAA Office of Hydrologic Development

The Hydrology Laboratory (HL) of the NWS Office of Hydrologic Development (OHD) is the research division responsible for developing scientific models and procedures for the NWSRFS. The Hydrology Laboratory is tasked with continually improving the DSS with new algorithms and assimilation of new or improved observations. Presently, the NWS uses satellite remote sensing data in their operational hydrologic modeling system on a limited basis to estimate observed precipitation. The Hydrology Laboratory is interested in extending the use of remote observations in several areas for improved estimates of evapotranspiration, frozen soil processes and mapping, and flood inundation mapping and monitoring. One area of interest is evaporation estimates from remotely sensed observations for use in the hydrologic modeling. NWSRFS has lost previously available functionality due to discontinued observations needed in evaporation computations. Replacement of those observations is HL's top priority, and that could be accomplished with remote observations from space. NASA's cloud mask product derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) can be used to replace discontinued ground observations of cloud cover. The cloud mask product will result in better quality input datasets for the NWSRFS and are expected to lead to improved flood forecasts.

1.3. Pilot Study Regions

The study area is shown in Figure 1. OHD has an ongoing distributed hydrologic modeling effort and would like to include it operational in the next generation of NWSTFS. One of OHD's internal modeling effort is concentrated over 23 watersheds in Texas (shown in purple in Fig 1. This modeling study involves the same underlying hydrologic models, however those are used in a distributed manner. In addition to this Texas effort, OHD is initiating a hydrologic model inter-comparison project (DMIP). In this effort, OHD would like compare the model performance of the NWSRFS with the other state of the art hydrologic models. One of the study areas for the DMIP is Blue River watershed at the Oklahoma Arkansas state line. The spatial and temporal extent of this study area has been redefined and enlarged to cover the 23 Texas watersheds in the OHD distributed hydrologic modeling study as well as the Blue River watershed. The cloud products generated through this effort will be assimilated into the modeling activities and the value will be quantified with a subset of these watersheds.

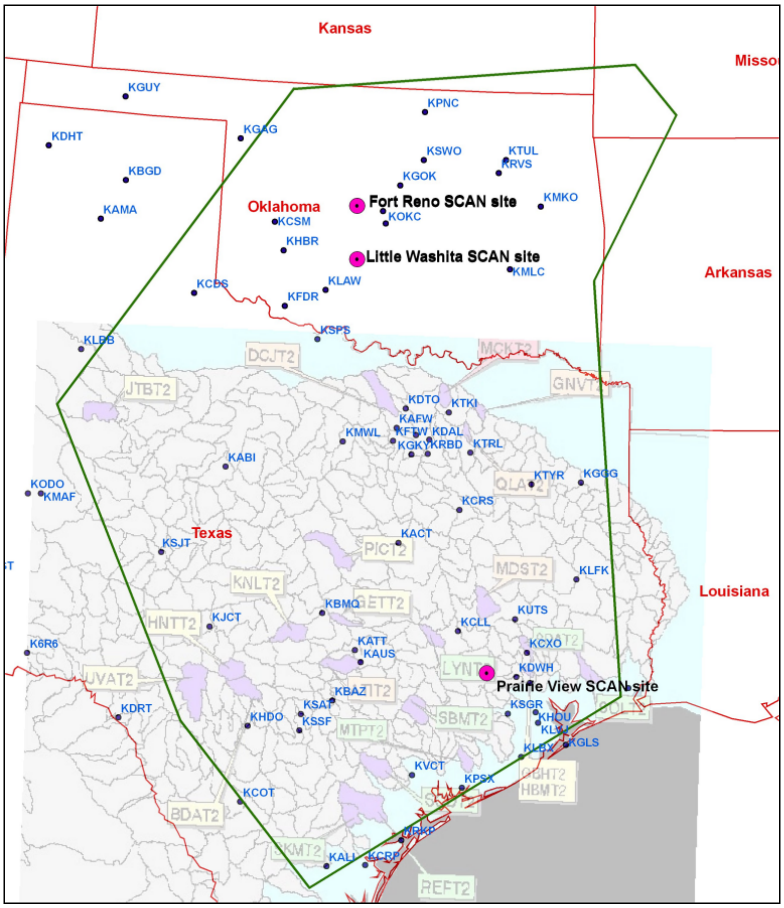

Figure 1. Map of the study area (green boundary). Watersheds of southern Texas are delineated. The 23 violet-filled watersheds are subject to hydrologic modeling by NOAA OHD. Three USDA SCAN sites are also shown as dark pink circles and labeled.

1.4. Systems Engineering Approach

The NASA Applied Sciences Program has defined an integrated systems solution for transitioning science products to operational applications (Figure 2). The framework defines a pathway by which NASA satellite observations and Earth science modeling products and/or predictions pass to a partner agency that utilizes a decision support system or tool to make informed policy or management decisions. NASA has chosen to follow a systems engineering approach to facilitate the transition of NASA ESE data to partner agencies. We will use this approach for the assimilation of NASA data into the NWSRFS and quantify the impact that ESE data products have on the streamflow estimation. The systems engineering approach to identify and assess the value of each data set leads to scalable, systemic, and sustainable solutions, which in turn contribute to the success of the application's goals. Figure 3 illustrates the systems engineering process and the four components: Evaluation, Verification, Validation, and Benchmarking. The process has built-in feedback loops that permit consideration of refinements or alternatives when criteria at each step fail to be met. Our plan to address each of the engineering components is described in more detail below.

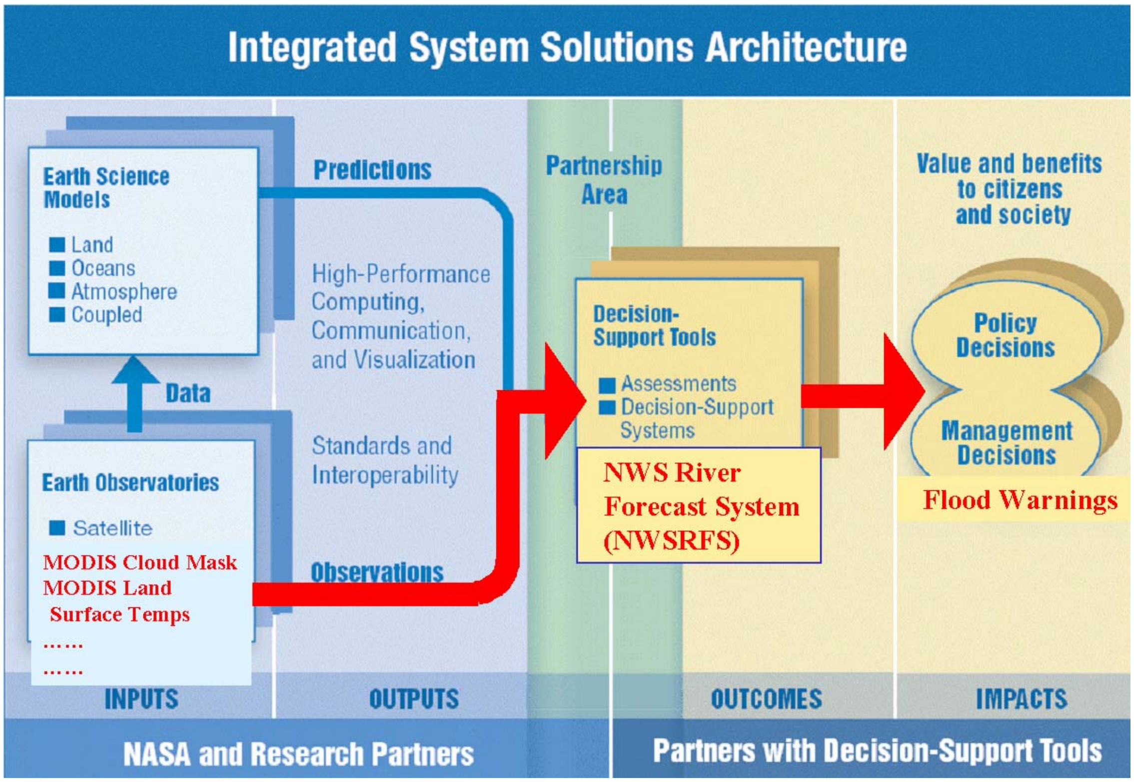

Figure2. The Integrated Systems Solution architecture underlying the activities of NASA's Applied Sciences Program defines pathways for transitioning science data and products to operational DSS. The pathway to be used in this project is superimposed in red.

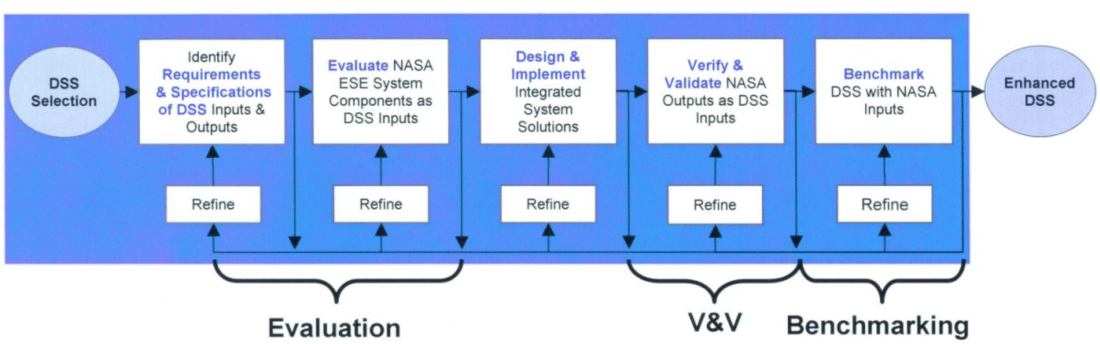

Figure 3. Earth science applications systems engineering process.

2. Overview of the DSS

2.1. Components of the NWSRFS

NWS River Forecast System is composed of a set of models and procedures. The hydrologic model and parameters are used in three components of the NWSRFS: the Calibration System, the short-term Operational Forecast System (OFS) and the long-term Ensemble Streamflow Prediction System (Figure 4). The Ensemble Streamflow Prediction System produces long-range forecasts from probabilistic predictions, and is designed to serve as a general guidance to the modeling groups as well as to the public at large. OFS produces short-term streamflow forecasts. These forecasts (highlighted in Figure 4) are the key output from the DSS that will be used in this project's benchmark process. The components in Figure 3 are designed to interact so as to avoid the creation of any bias between model calibration and short and long-term forecasting. RFCs have spent considerable time calibrating the hydrologic models so as to achieve a delicate balance of parameter estimation to maintain consistency between the systems.

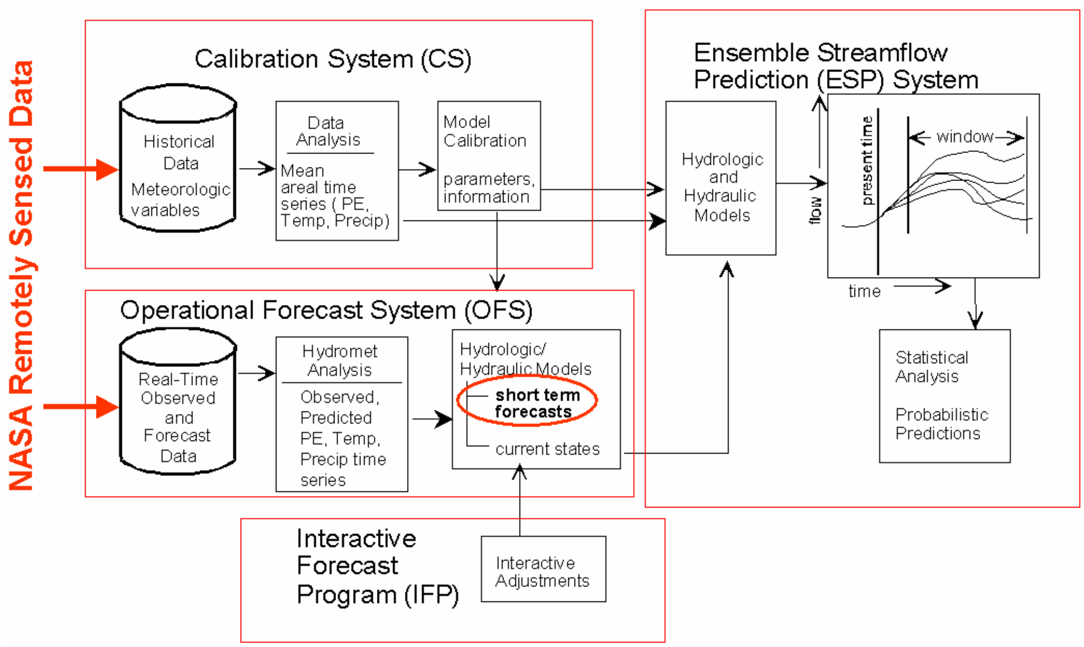

Figure 4. Schematic of the NWS River Forecast System components.

NWS has divided the U. S. into 13 hydrologic regimes, each under the domain of one of the RFCs. NWS RFCs subdivide their entire spatial domain into subwatersheds. Subwatersheds are the smallest modeling unit (spatial extent of few tens to a few hundreds of km^2). Connectivity diagrams for each domain link the subwatersheds with the domain discharge locations. Forecasted streamflow is computed for each subwatershed for each time period (typically 6 hours) using forecasted precipitation and state variables stored from the previous runs. Hydraulic models transport water from the subwatershed outlet to the discharge location.

Within NWSRFS, RFCs depend on a highly parameterized spatially-lumped soil moisture accounting model (Sacramento Soil Moisture Accounting model (SAC-SMA), Burnash et al., 1973). Inputs to the model include precipitation and temperatures. The snow model (Anderson, 1973) uses temperature as an index for the amount of energy exchange at the snow-air interface. It contains accumulation and melt components. Potential evaporation (PE) is an external input to the SAC-SMA, and used as a "soil dryer" (a term RFCs use for PE). A consumptive use adjustment factor is used to modify the PE to account for transpiration. The various parameters used in the modeling system are carefully calibrated for each subwatershed.

Historically, RFCs have used three sources of solar radiation data to compute potential evaporation (Lindsey and Farnsworth, 1997) using the Penman equation (Penman, 1948, Lamoreux et al., 1962): 1) direct measurements from pyranometers, 2) estimates based on percent sunshine (Hamon et al., 1954), and 3) estimates of solar radiation from sky cover (Thompson, 1976). The direct solar radiation observations from pyranometers were not available on an operational time frame. Sky cover estimates were derived from manual cloud cover observations. The percent sunshine method agreed best with the direct measurements, but these observations also were not available operationally. Consequently, in 5 of the 13 RFCs sky cover observations were used in model calibration. The other 8 RFCs chose to use mean monthly PE estimates to force the SAC-SMA model. All estimates of long term PE have been adjusted to agree with the NWS's "standard" PE atlas (Farnsworth and Peck, 1982).

2.2 Gaps in Meeting DSS Needs

The Automated Surface Observing System (ASOS) was originally developed by the Federal Aviation Administration (FAA) to aid aircraft navigation. It was subsequently adopted by the NWS and has replaced manual weather observations. ASOS observations include data from Ceilometers, but whereas manual observations recorded cloud information at all levels, ASOS data does not report sky conditions above an altitude of 12,600 feet. While for FAA purposes, cloud characteristics may not be important above 12,600 feet, they are of critical importance when one is quantifying surface observations, such as incident solar radiation (Unger, 1992). Consequently, the RFCs have lost the ability to reliably compute daily PE to operationally force the SAC-SMA model in a manner consistent with the historical data used for model calibration. Thus, RFCs are faced with a rare situation in which the forecasters have lost previously available functionality (Lindsey and Farnsworth 1997; Schreiner et al., 1993; Unger, 1992). As a result, RFC hydrologists have largely reverted to using long-term climatic monthly mean PE values derived from pan observations**.** Lindsey and Farnsworth (1997) reported that the use of monthly values leads to significantly degraded streamflow simulations. Spatial average of PE is produced for each subwatershed by assigning user-specified or Theissen weights (Maidment, 1993) to each adjacent observation site. The result is a single spatially-weighted average value of PE for the subwatershed derived purely from climatological means.

The NWS Advanced Hydrologic Prediction Services (AHPS) is a recently implemented, congressionally funded, service improvement program. It will expand the existing capabilities of the NWSRFS and the NWS Office of Hydrologic Development (OHD) has placed a high priority on national implementation of AHPS. As part of the AHPS improvements, HL is encouraging the use of distributed hydrologic models in operational hydrologic modeling. HL has developed a spatially-distributed version of the SAC-SMA (the HL-Research Modeling System, RMS, Koren et al., 2004). HL-RMS will be run on a 4 km grid making it consistent with the NWS NEXRAD-based radar rainfall data. HL plans continued, rigorous testing of HL-RMS at selected testbed watersheds with results from other distributed hydrologic models via DMIP. Upon thorough analysis and testing, HL-RMS will become a part of NWSRFS. HL's shift toward spatially distributed gridded models is particularly conducive to the incorporation of remotely sensed data into NWSRFS.

2.3. Meeting Technical Requirements with NASA Products

The Evaluation process involves identifying candidate remote sensing or Earth science data sets for use in the partner DSS and assessing their technical feasibility through definition of requirements and specifications. Presently, NASA's assets include 18 satellites providing an array of measurements from which a larger number of Earth science products are produced that enable the study of Earth as an integrated system. These assets are documented in several NASA publications and in a Knowledge Base developed specifically for NASA's Applied Sciences Program that catalogues available products and associated potential applications. NASA has also conducted a survey of DSSs that may benefit from use of NASA data and conducted an initial Evaluation to determine how well some of these data meet the partner agencies requirements (NASA, 2003).

The NWS RFC's decision support system was not included in the results of NASA's initial survey of agencies that could benefit from NASA products. Subsequently, this team was funded by NASA to conduct a preliminary assessment of the potential for NWSRFS to benefit from NASA's remotely sensed data. During the course of our Evaluation, several candidate data sets have quickly surfaced as responsive to our needs: cloud mask products to help restore lost functionality, LST for improved spatial estimation of PE, vegetation indexes, and digital elevation data. Long-term statistical stability of parameters is a critical data requirement for HL and RFCs. Because of the effort involved, RFC's are reluctant to recalibrate the operational DSS. The same sets of parameters are used in all three components of the NWSRFS. Thus, hydrologic state variables estimated by assimilating NASA remotely sensed data sets or products must be statistically indistinguishable from the long-term historic time series of those variables. Otherwise, recalibration will be required.

3. Consideration of NASA Inputs

3.1. Potential NASA Satellite Derived Products for OHD DSS

As noted above, RFCs have lost the ability to reliably compute daily PE to operationally force the SAC-SMA model in a manner consistent with the historical data used for model calibration. Consequently, recovering this lost functionality on an operational basis is a high priority for the RFCs and an easier requirement to meet as it can be utilized almost directly. Initially, data from the Geostationary Operational Environmental Satellite (GOES) cloud cover data were used to augment the ASOS Ceilometer data, but Lindsey and Farnsworth (1997) concluded that this approach contained uncertainties that were too difficult to define for solar radiation. However, some researchers have tried this approach with success. Schreiner et al. (1993) found good agreement between manual sky cover estimates and satellite enhanced ASOS observations. Menzel et al. (1998) also report significant success. Belcher and DeGaetano (2004) used GOES satellite-enhanced ASOS observations to compute solar radiation estimates. The authors report that their method produces results that are consistent with pre-ASOS manually-derived solar radiation.

Cloud cover products are available as standard products from MODIS and GOES. The science teams responsible for these products have gone through a rigorous validation process, and have certified these products as validated (for example, for MODIS see Ackerman et al., 2002). GOES data are available every hour at a nominal resolution of 10 km (for the sounder data). MODIS sensors are onboard two satellites, Terra and Aqua. The nominal overpass times for Terra and Aqua are 10:30 and 1:30 during the day and night for a total of four daily overpasses. Many of the MODIS products have a spatial resolution of 1km, including the cloud mask. The 1km resolution of MODIS data will enable discrimination among adjacent subwatersheds (each with a spatial extent of a few tens to a few hundreds of km^2) in a more quantitative fashion as compared to the GOES data. We believe that the MODIS cloud cover can be used to produce daily PE estimates internal to NWSRFS within 5% of the long-term average evaporation for a given station. Since this project relies exclusively on use of NASA data to feed into the existing potential evaporation estimation techniques within NWSRFS, we can only speculate on the accuracy based on the analysis performed as a part of the preliminary assessment. Since the functionality is present in the existing operational models, long-term statistical properties of evaporation shall be used to define specifications for cloud cover products.

4. Conclusions

4.1. DSS Summary and Potential NASA inputs

NOAA has a mandate for providing the nation with operational streamflow forecasts, which is enforced using NOAA's hydrologic modeling framework NWSRFS (National Weather Service River Forecast System). NASA satellite-based Earth Science observations can be effectively utilized to improve key modeling components used within NWSRFS.

Improvement in one such modeling component is evaporation estimates from remotely sensed observations for use in the hydrologic modeling. NWSRFS has lost previously available functionality due to discontinued observations needed in evaporation computations. Replacement of those observations is a priority for HL, and that could be effectively accomplished with remotely sensed observations. NASA's cloud mask product derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) will provide an effective replacement of discontinued ground observations of cloud cover. This effort is directly associated with the NASA Water Management Program's roadmap by assimilating NASA's observational capabilities to improve the accuracy of water management predictions of another federal agency in operational decision-making.

4.2 Recommendations

Verification is a life cycle process to ensure the products being developed meet the stated functional and performance specifications defined in the Evaluation Process. Validation is the process by which we determine if the NASA data product will effectively serve the partner's functional requirements. Both processes must be addressed in close collaboration with the partner agency. These processes are system checks that the product is on target towards a successful outcome. Verification or Validation failure results in a pathway that loops back to the Evaluation process for consideration of refinements or alternatives (Figure 3). Because of the effort involved, RFCs are reluctant to recalibrate the operational DSS. Thus, the most important criterion for verification is to avoid the necessity to recalibrate, which is required if the statistical range of the remotely sensed state variable or parameter exceeds the historical statistical limits. However, meeting these historical limits does not guarantee improved streamflow forecasts.

Consider the NWSRFS requirement for cloud cover information to estimate daily PE. The manual observations were replaced with automated estimation of cloud cover with the implementation of ASOS, which only estimates clouds below an altitude of 12,600 feet. Clouds above that altitude are not detected, which leads to significant errors (Menzel et al., 1989; Unger, 1992; Schreiner et al, 1993; Lindsey and Farnsworth, 1997; Menzel et al., 1998; Belcher and DeGaetano, 2004). Consequently, because ASOS estimates of cloud cover do not meet specifications, the RFCs do not routinely use these ASOS cloud cover measurements in their computation of PE. Instead, they depend on climatic monthly means discussed earlier. Although MODIS cloud cover products are independent of altitude, they are only available twice daily and therefore do not meet specifications either. However, the approach that would meet the RFCs specifications would be a product that combines the virtues of both ASOS and MODIS cloud cover products. This will serve as the Verification.

4.3 Next Steps

To benchmark the utility of NASA remotely sensed data in NWSRFS, an affiliation with an ongoing OHD effort in the hydrologic modeling enhancement or validation would be essential. OHD is initiating a hydrologic model inter-comparison project (DMIP). In this effort, OHD will compare the NWSRFS model with the other state of the art hydrologic models. Hydrologic model performance in the absence and presence of NASA datasets will serve as a quantifiable benchmark to assess the utility of NASA data in the NWSRFS.

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